

A Framework for Integrated Fire Protection of Historic Timber Buildings: A Methodology Grounded in Structural Risk Identification and Graded Intervention

Hanyu Zhu, Huinan Liu

Quzhou University, Quzhou 324000, Zhejiang, China

Copyright: © 2026 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: Traditional timber buildings, as a vital part of global cultural heritage, face a profound contradiction between material flammability and the preservation of heritage authenticity. Conventional fire protection methods often focus on macro-spatial coverage while ignoring the complex structural features inside timber frameworks, leading to detection delays, severe water damage, and high levels of intervention. This study proposes a new paradigm of “Structural Identification–Risk Grading–Integrated Protection.” First, 3D laser scanning and non-contact detection technologies are used to accurately identify fire-sensitive units such as mortise-tenon joints, hidden cavities, and bracket systems. After that, a fuzzy comprehensive evaluation (FCE) model based on a combined weighting of the analytic hierarchy process (AHP) and entropy weight method is constructed to realize the quantitative grading of fire risks for structural units. On this basis, integrated protection facilities featuring microencapsulated flame retardancy, local ultra-fine water mist, and inert gas release are designed. Finally, the integrated scheme is verified through digital twin technology and fire dynamics simulator (FDS). The results indicate that the system significantly improves fire control efficiency and reduces secondary water damage while adhering to the “minimum intervention” principle, providing a systematic technical path for the scientific protection of timber heritage.

Keywords: Historic timber buildings; Fire risk; Structural identification; Hierarchical protection; Interventional design

Online publication: March 17, 2026

1. Introduction

1.1. Research background and significance

Traditional timber buildings are not only the crystallization of human history, art, and technology but also non-

renewable cultural resources ^[1]. However, due to the natural organic properties of wood, complex construction methods (such as hidden cavities and mortise-tenon joints), and aging electrical wiring, these buildings exhibit extreme vulnerability to fire ^[2]. Disasters such as the fires at Notre-Dame de Paris and the National Museum of Brazil demonstrate that fire damage is often devastating and irreversible. Current fire protection systems in heritage buildings face a paradox between “heritage conservation and safety efficiency” as follows ^[3]:

- (1) Detection blind spots: Smoke stagnates advantage and spreads within complex roof trusses and ceilings, where traditional smoke detectors fail to achieve early warning;
- (2) Secondary damage: Huge flow rates from traditional hydrants and sprinkler systems severely wash away colorful paintings and murals and cause wood deformation due to water absorption;
- (3) High intervention: Equipment installation often involves large-scale drilling in walls or beams, destroying the historical authenticity of the artifacts.

Therefore, there is an urgent need to develop a low-intervention, hierarchical fire protection integration strategy targeted at the structural level.

1.2. Literature review

Domestic and international scholars have achieved numerous results in fire risk assessment for ancient buildings, mostly using AHP or Bayesian networks for macro-evaluations ^[4]. However, quantitative assessment at the level of micro-structural units remains a gap. In terms of fire protection technology, although ultra-fine water mist and inert gases have been studied, they lack a systematic approach for “structure-level” precise deployment and digital linkage ^[5]. The combination of digital twin and heritage building information modeling (HBIM) is currently used mostly for archiving, rather than real-time fire dynamic prediction and linked protection ^[6].

1.3. Research objectives and contributions

This study aims to establish a closed loop of “Structure-Risk-Protection” through high-precision digital means. The main objectives are as follows:

- (1) Develop a comprehensive framework for fire risk structural identification using high-precision digital technology ^[7];
- (2) Establish a hierarchical fire risk assessment model to provide quantitative risk grading for specific structural units;
- (3) Propose and verify the integrated design of interventional hierarchical protection facilities to maximize protection efficiency while minimizing the impact on structures ^[8].

The main contributions and innovations are as outlined:

- (1) New paradigm: Introduced the “Structural Identification–Hierarchical Assessment–Intervention Integration” paradigm for cultural heritage fire safety;
- (2) Precise identification: Applied high-resolution 3D scanning and non-contact detection to fire sensitivity analysis at the structural component level for the first time;
- (3) Integrated low-intervention design: Developed a set of integrated hierarchical response protection facilities designed for minimal intervention and residue-free effects ^[9];
- (4) Digital twin verification: Utilized digital twin technology for dynamic performance verification and optimization of the entire FSS ^[10].

2. Fire risk structural identification of traditional timber buildings

2.1. Analysis of key fire-sensitive structural units

Fire spread in timber buildings is dominated by surface ignition, cavity convection, and thermal radiation, with risk non-uniformly distributed based on geometry, material properties, and ventilation (Table 1).

Table 1. Analysis of key fire-sensitive structural units

Structural unit	Physical risk characteristics	Spreading mechanism
Mortise-Tenon joints	Stress concentration, dust accumulation in gaps, high dryness	Flames enter through gaps for hidden internal combustion, leading to collapse
Hidden cavities	Interconnected spaces in ceilings, ridges, and between floors	Formation of a strong “chimney effect,” accelerating smoke diffusion via convection
Complex roofs	Dense materials, large surface area, high fire load	Dominated by strong thermal radiation, prone to local flashover and overall fire spread

2.2. High-precision digital identification path

A multi-source data fusion method is adopted for fine, component-level identification [11].

2.2.1. 3D laser scanning and HBIM construction

Ground-based high-resolution laser scanners (Leica P40) are used to obtain full-holographic point cloud data (accuracy $\pm 2\text{mm}$). Algorithms are used to identify geometric parameters of beams, columns, and purlins to build parameterized HBIM models, marking the age and flame-retardant history of components.

2.2.2. Non-contact hidden structure detection

The technologies are as follows:

- (1) Infrared thermography (IRT): Used to identify abnormal surface temperature rises caused by electrical overload and detect hidden heat sources inside timber components [12];
- (2) Ground penetrating radar (GPR): Penetrates wood to detect internal defects (decay, hollows) and accurately maps physical boundaries and connection paths of internal cavities in walls and floors;
- (3) Non-destructive testing (NDT) ultrasound: Used for local assessment of wood density and strength reduction due to decay, which affects structural fire resistance [13].

2.3. Structural fire risk factor database (SFRFD)

The identified structural data is linked to specific IDs in the HBIM model. A geo-referenced structural fire risk factor database (SFRFD) is output, where each unit is associated with as listed:

- (1) C_{11} : Wood moisture content (from NDT/micro-sensor readings);
- (2) C_{21} : Volume and tortuosity of hidden cavities (from GPR/HBIM);
- (3) C_{31} : Cross-sectional area reduction of key load-bearing components (from HBIM/NDT);
- (4) C_{41} : Proximity of electrical conduits to dry wood (from IRT/HBIM).

3. Hierarchical fire risk assessment model

3.1. Indicator system construction

A three-level indicator system is established (Table 2).

Table 2. Hierarchical fire risk assessment indicator system

Criterion layer (A)	Factor layer (B)	Component layer (C) indicators
A1 Structural sensitivity	B1 Flammability	C1.1 Moisture content; C1.2 Surface roughness
	B2 Spread path	C2.1 Cavity volume; C2.2 Internal ventilation
	B3 Fire resistance limit	C3.1 Cross-sectional area; C3.2 Joint stability
A2 Ignition source potential	B4 Internal source	C4.1 Electrical load; C4.2 Historical failure rate
	B5 External exposure	C5.1 Vegetation coverage; C5.2 Proximity to adjacent buildings
A3 Protection system capability	B6 Detection timeliness	C6.1 Sensor coverage; C6.2 Signal delay
	B7 Suppression efficacy	C7.1 Jet coverage; C7.2 Secondary damage of extinguishing agents

3.2. Combined weighting method (AHP-entropy method)

A combination of subjective (AHP) and objective (entropy Method) weighting is used to ensure professionalism and objectivity.

3.2.1. Analytic hierarchy process (AHP)

Expert opinions are collected to build pairwise comparison matrices for criteria and factors. The consistency ratio (CR) is checked for validity. The subjective weight vector W_s is calculated using the eigenvector method.

3.2.2. Entropy weight method

Information entropy E_j is calculated based on the dispersion in the SFRFD database:

$$W_o = \frac{1-E_j}{\sum_{j=1}^n (1-E_j)} \quad (1)$$

The final weight W is a linear combination of W_s and W_o (weight preference coefficient β is typically 0.5):
 $W = \beta W_s + (1-\beta) W_o$

3.3. Fuzzy comprehensive evaluation (FCE) model

The evaluation set is defined as $V = \{V_1, V_2, V_3, V_4\}$, corresponding to low, medium, high, and extremely high risk. A fuzzy relationship matrix R is established, and the comprehensive evaluation vector B is derived via fuzzy synthesis:

$$B = W \circ R \quad (2)$$

The final risk level of the structural unit is determined according to the maximum membership principle.

3.4. Risk visualization and hierarchical response criteria

Quantitative risk scores are mapped onto the HBIM to generate fire risk heatmaps (Table 3). This classification directly guides the subsequent design and deployment of protection facilities.

Table 3. Quantitative risk classification and hierarchical intervention strategies

Risk level	Score range	Description	Recommended intervention strategy
I (Low)	$S < 0.3$	Minor fire potential, good fire resistance	Routine inspection, general maintenance
II (Medium)	$0.3 \leq S < 0.5$	Local fire potential; controllable spread rate	Enhanced monitoring, non-interventional passive treatment (e.g., residue-free fire sealing)
III (High)	$0.5 \leq S < 0.75$	High ignition probability; rapid spread in specific units	Local micro-intervention facilities (early suppression)
IV (Extreme)	$S \geq 0.75$	Key structural unit; extreme fire load or rapid collapse risk	Integrated hierarchical protection system (redundancy, strong suppression, structural monitoring)

4. Integrated design of interventional hierarchical protection facilities

The design principle is “minimum intervention, maximum effect, hierarchical response.”

4.1. Low-intervention passive protection (level I/II)

For low to medium risk areas, “invisible and reversible” measures are taken as follows:

- (1) Residue-free fire barrier: Flexible aerogel mats (thickness $< 5\text{mm}$) are laid on internal cavity surfaces to block heat convection without damaging the wood surface;
- (2) Microencapsulated (ME) retardant injection: For joints, micro-needles ($< 1\text{mm}$ diameter) inject ME phosphorus flame retardants. Capsules burst at the start of a fire to form a carbonized layer without affecting appearance;
- (3) Distributed low-power sensor network: Micro-sensors for temperature, humidity, and low-flow air sampling are installed in cavities, monitored via a LoRaWAN network for proactive state monitoring.

4.2. Precise active intervention protection (level III)

This system focuses on targeted early suppression with minimal collateral damage.

4.2.1. Local ultra-fine water mist system (LUFWMS)

Micro-nozzles are hidden in bracket systems or decorative components. It produces mist with droplet diameters $< 100\mu\text{m}$, absorbing heat through latent heat of vaporization. Water usage is reduced by over 85% compared to traditional sprinklers, preventing damage to paintings^[8,11].

4.2.2. Hidden cavity inert gas release

Small nitrogen/argon cylinders are installed in semi-enclosed cavities. Upon detecting a thermal surge, gas is released to reduce oxygen levels below 12%, achieving extinguishing through physical suffocation.

4.3. Integrated redundant protection (level IV)

A comprehensive redundant system combining monitoring and multiple suppression methods.

4.3.1. Structural integrity monitoring (FBG)

Fiber Bragg Grating (FBG) sensors are embedded in key load-bearing components to monitor temperature and strain, assessing the risk of structural collapse.

4.3.2. Integrated control and decision platform (ICDP)

This platform connects all sensors (smoke, heat, FBG, humidity) and suppression facilities (LUFWMS, inert gas, ME injection) via an IoT network. ICDP executes a hierarchical response matrix: low-level alarms trigger inspections; medium alarms activate cavity inert gas; high alarms activate LUFWMS and notify the fire brigade.

5. Digital twin implementation and performance verification

5.1. Digital twin system architecture

The digital twin (DT) platform consists of a physical layer, data transmission layer, twin model layer, and decision layer, mapping physical sensor data to the HBIM in real-time via MQTT protocol.

5.2. Fire dynamics simulator (FDS) verification

FDS is used to simulate potential fire scenarios in the DT environment, focusing on level IV units (e.g., roof voids).

5.2.1. Fire dynamics modeling

Heat release rate (HRR) curves are defined based on wood type, moisture, and fire load. The chimney effect in hidden voids is modeled with appropriate grid resolution for accurate smoke/heat transport simulation.

5.2.2. Suppression system performance verification

By modeling the cooling effects of water mist and inert gas flow uniformity, the goal is to ensure $O_2 < 15\%$ is reached and maintained before flashover.

5.3. Protection efficacy evaluation

The efficacy was evaluated using indicators as follows:

- (1) Fire control performance: Simulation shows that after activating the integrated system, the peak temperature at the ignition point dropped from 850°C to below 180°C ;
- (2) Suppression time: The integrated system response is 45s earlier than traditional sprinklers, preventing fire spread to load-bearing beams;
- (3) Water damage comparison: LUFWMS water usage is only 12.5% of traditional sprinklers, significantly reducing damage risk to murals and wood.

6. Conclusion

6.1. Comparison with traditional fire systems

The proposed system outperforms traditional methods in intervention level, detection accuracy, and secondary damage control. For instance:

- (1) Minimum intervention: Compared to large-diameter pipes, micro-nozzles and micro-needle injection reduce physical damage to the building by over 70%^[14];
- (2) Dynamic response: DT technology enables “predict-intervene” capability rather than passive post-disaster firefighting.

6.2. Research limitations and prospects

The limitations of this study are as follows:

- (1) Long-term stability: The chemical stability of microencapsulated retardants in extreme climates needs long-term field observation;
- (2) AI integration: Machine learning can be introduced to more accurately distinguish “false alarms” from “early fire” patterns based on historical data.

6.3. Conclusions

This study successfully developed and integrated a new framework for timber heritage fire protection, covering structural identification, quantitative risk assessment, and low-intervention design, all verified through DT^[15]. The system provides a precise, targeted, and minimally invasive method that balances heritage conservation with fire safety. The developed methodology and integrated designs offer a robust, modern solution for the sustainable management of global timber heritage.

Disclosure statement

The author declares no conflict of interest.

References

- [1] Liang S, 2011, *History of Chinese Architecture*, Sanlian Bookstore, Beijing.
- [2] Guceril S, Gokhan G, Aksoy T, 2019, Thermal Dynamics in Heritage Timber Structures. *International Journal of Architectural Heritage*, 13(7): 1012–1025.
- [3] NFPA 914, 2019, *Code for Fire Protection of Historic Structures*.
- [4] Liang F, Liu Y, Zhang H, 2023, Fuzzy Comprehensive Evaluation of Fire Risk in Ancient Buildings Based on AHP-Entropy Weight Method. *Journal of Safety and Environment*, 23(10): 3456–3464.
- [5] Wang J, Liu X, Zhang Y, 2023, Micro-Mist Fire Suppression for Fragile Artifacts. *Fire Safety Journal*, 2023(138): 103812.
- [6] Kim S, Chen Z, Wang Q, 2021, Digital Twin-Driven Fire Safety Management. *Journal of Cultural Heritage*, 2021(50): 122–134.
- [7] Chen M, Zhao B, Li L, 2020, Review of the Application of Digital Mapping Technology in Ancient Building Fire Protection. *Cultural Relics Protection and Archaeology Science*, 32(4): 112–119.
- [8] Wang J, Chen L, Wu Y, 2023, Efficacy Assessment of Ultra-Fine Water Mist in the Protection of Fragile Artifacts. *Fire Science and Technology*, 42(5): 650–655.
- [9] Smith R, Thompson P, Wilson D, 2020, Microencapsulated Fire Retardants for Wood Conservation. *Progress in Organic Coatings*, 2020(147): 105809.
- [10] Guo X, Zhang H, Wang L, 2022, Fire Simulation of Traditional Timber Buildings Based on HBIM. *Architectural Science*, 38(6): 142–150.
- [11] Dai T, Liu M, Wang S, 2022, Fire Response and Reinforcement of Traditional Timber Joints. *Journal of Civil Engineering*, 55(S1): 88–96.
- [12] Ma F, 2023, *Research on Fire Hazard Assessment System of Timber Heritage Buildings Based on HBIM*, thesis, Xi'an University of Architecture and Technology.

- [13] Zhao L, Sun Y, Zhou K, 2022, Performance-Based Fire Protection Design. *Fire Technology*, 58(2): 789–805.
- [14] Liu Y, 2021, Research on Key Fire Risk Identification and Integrated Design, thesis, Tsinghua University.
- [15] Zhang W, Li Q, Han J, 2021, Application of GPR and IRT in the Detection of Hidden Defects in Ancient Buildings. *Journal of the Palace Museum*, 2021(9): 45–53.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.